Final Report

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Executive Summary

Our research at the University of South Carolina, as part of the Electric Ship Research and Development Consortium, has advanced technologies and methods applicable to electric ships in three broad areas: 1) early-stage ship design tools, 2) control and modeling of electric power systems, and 3) cooling methods for electric ship systems.

In the area of early-stage ship design tools, we accomplished two main objectives: We enhanced the scope and capabilities of S3D (a distributed, collaborative early stage design environment), and we defined a process for integrating S3D technologies into NSWC's LEAPS-centered toolkit. The S3D environment serves as an agile development testbed for rapidly designing and evaluating new ship design concepts and evaluation of the system-wide benefits of new power technologies or new design concepts that exploit those technologies.

Research in Control and Modeling of Power Systems was driven by a desire for ships to exploit the powerful benefits of an extensively-interconnected, electronically-mediated power distribution architecture. This architectural concept enables unique opportunities to control power flows and to limit fault currents, but it also presents challenges with respect to ensuring stability and achievement of high dynamic performance objectives. Advances were achieved in five areas: 1) methods for measuring power system impedances to improve the control of ship electric systems, 2) methods for controlling power systems based on those measured impedances, 3) definition of a framework for evaluating the performance of distributed energy storage concepts, 4) control-based (breakerless) methods for managing short circuit faults in MVDC Systems, and 5) modeling of SiC-based electronic power converters to support accurate scalable models in S3D.

Research in advanced thermal management followed three tracks. We developed models of thermal system components that are suitable for use in early stage design studies. We developed reference designs for advanced ship thermal management systems (this work was strongly collaborative with MIT & FSU). We studied the application of advanced two-stage cooling technologies to the cooling of electronic power converters for ship electrical systems.

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Introduction

This report describes activities and outcomes from a three-year research program conducted at the University of South Carolina in collaboration with team members at other ESRDC-affiliated schools. At USC, our efforts focused on three broad topics: 1) early-stage ship design tools, 2) advanced electric power systems control and modeling, and 3) applications of advanced cooling methods in electric ship systems.

Research in **early-stage ship design tools** produced significant progress towards its two main objectives: *enhanced functionality* of the distributed, collaborative S3D early stage design environment, and *definition of a process for integrating* S3D technologies into NSWC's LEAPS-centered toolkit. Several major functional objectives were accomplished including: development of a capability to exercise and evaluate designs against missions, improvements to tools for designing distributed systems, development of several reference or exploratory models of advanced electric ships, and providing support for our ESRDC partners as they developed additional capabilities such as for sizing and routing of electric power cables, and developing scalable models of electric machinery. Furthermore, we used the developing S3D environment to evaluate and demonstrate the advantages and disadvantages of several advanced ship technologies.

The developed S3D environment carries three significant benefits:

1. It serves as an agile development testbed for rapidly brainstorming, designing, developing, and evaluating new designer tools and new design processes.
2. It serves as a first testbed for ship and systems concepts, allowing exploration and evaluation of the system-wide benefits of new power technologies or of new design concepts that exploit those technologies.
3. It serves as a source of ship design tool technologies from which selected technologies can be mined (by the Navy and others) for subsequent refinement and insertion into the NSWC's LEAPS-centered design toolkit.

Research in **Power Systems Control and Modeling** was driven by a desire to exploit the potentially powerful benefits of an extensively-interconnected, electronically-mediated power distribution architecture. This architectural concept enables unique opportunities to control power flows and to limit fault currents, but it also brings challenges with respect to ensuring stability and meeting objectives for high dynamic performance.

This research accomplished five main objectives. It:

1. Improved the methods for measuring power system impedance so that impedance characteristics can be considered and used to improve the control of ship electric systems, and to improve the performance of power hardware in the loop simulations.
2. Developed new impedance-based methods for controlling ship electric systems.
3. Developed a framework for evaluating the performance of distributed energy storage concepts
4. Improved the reach and understanding of breaker-less, control-based methods for managing short circuit faults in MVDC Systems.

5. Developed models of SiC-based electronic power converters that are appropriate for early-stage system-level design studies.

Research in **advanced thermal management** followed three tracks. The first involved developing models of thermal system components that are suitable for use in early stage design studies. The second involved developing reference designs for advanced ship thermal management systems (this work was strongly collaborative with MIT & FSU). The third studied application of advanced two-stage cooling technologies, developed in 6.1 research programs [1,2], to the cooling of electronic power converters for ship electrical systems.

This research accomplished six main objectives. It:

- Developed S3D-compatible models for state-of-the-art heat exchangers and air cooling technologies based on surveys of the best published models and correlations.
- Worked in collaboration with FSU & MIT to develop a core group of models of HVAC components and of highly efficient vapor-compression refrigeration cycles suitable for early stage ship design studies.
- Developed a hardware testbed for two-phase heat transfer and heat flow as needed to calibrate and validate system-level models. Data from the testbed proved that heat transfer rates were close to those obtained by applying Nusselts' theory in filmwise condensation.
- Developed a reference simulation model of a two-phase cold plate for an electronic power converter that showed the possibility to substantially reduce the wall temperature - by up to 40 C - compared to single-phase cooling.
- experimentally validated models of two-phase heat exchangers including correct prediction of required flow rates and fluid pumping powers.

Development of Early stage ship design tools

This work addressed the Navy's compelling need for better early-stage design tools that will dramatically reduce the costs and improve the quality of the ship designs by permitting rapid and intuitive exploration of a wide design space [3]. The S3D software developed under this program offers: high levels of effective collaboration across the major disciplines; capture and reuse of a system knowledge and system design data, and the possibility to apply that knowledge and data in future system designs; higher fidelity in system definition which enables higher confidence in performance assessments and in budget commitments; rapid analysis of power flows under various operating conditions; a route for extending concept design phase models and simulations to more detailed models and simulations for subsequent studies of the most promising concepts; the promises of higher-value final ship designs, and reductions in cost and risk.

Our development of early stage ship design tools was highly collaborative; participants included researchers from all of the ESRDC schools including the University of South Carolina, Florida State University, Massachusetts Institute of Technology, Mississippi State University, Purdue, and the University of Texas. South Carolina coordinated and led the software development.

Initial development of the S3D design environment, including some capabilities for developing ship arrangements, and defining distributed mechanical, electrical, and piping systems was done under ONR grant # N00014-08-0080 during the 2008 to 2014 time frame. An ESRDC S3D demo and workshop [4], conducted in September 2013, near the end of that earlier grant, collected a list of improvements that became instrumental in defining the R&D plan for the work reported under this subsequent grant. Additional needs for new capabilities and functionalities were identified during consultations with ESRDC researchers, NSWC personnel, and ONR personnel. The improvements and new functionalities, addressed under the current grant, included:

- Extending Software Methods that Support Concurrent Design
- Extending Core Capabilities in Visualization
- Analyzing Performance across Missions - Methods, Metrics, and Mission Definition
- Integrating Distributed Systems into the Ship
- Increasing freedom in the Design Space via Equipment Scaling
- Rapidly Generating Concept Designs across Disciplines

Also, a human factors study [5] was conducted early in the period of performance to provide further guidance for the tool development. Finally, the development goals constantly evolved as new functionalities (and component models) were identified as necessary to support ESRDC or Navy needs.

Our development of these early stage design tools respected the Navy's enormous investment in its set of LEAPS-integrated design tools, as well as the ultimate need to integrate our new tools with that LEAPS-centric tool set. A two-pronged approach supported continuing development of the S3D environment and concurrent migration of S3D capabilities and technologies into the Navy tool set.

In the first prong, we continued development of the collaborative, networked, distributed S3D system design environment by exploiting C# and .NET framework. This enabled rapid code development to support fast, agile, and wide-ranging exploration of design processes and collaboration methods. This approach permitted the development team to be as responsive as possible to the rest of the ESRDC team as the ESRDC team invented, developed and used the tools in test cases.

In the second prong, we invested significant effort towards adapting and migrating the most-mature S3D tools into a LEAPS-compatible application suitable for use in upcoming Navy design efforts.

Extending Core Capabilities in Visualization

Dynamic rendering of 3D objects on 2D displays over a web interface helps designers in each discipline to visuallize the information that they will need to close a design. The physical geometry and locations of decks, bulkheads, and equipment all have significant impacts on the design of ship systems. Once the user positions equipment, the visualization tool captures geometric data for each piece of placed equipment. This is true also for distributed systems such as cables, pipes, ventilation ducts, and shafts. The main objective of this task was to provide the discipline specific tools the ability to use this geometry data in order to produce more accurate analyses and to close a design faster. These refined estimates of cable lengths can reduce the margins typically allowed by electrical engineers when sizing for capacity and thus lead to earlier convergence on a better and more-certain design.

A second objective of this task was to permit a user to rapidly improve and refine a design concept via semi-automated establishment of service buses, cable runs, piping runs, ventilation, and shafts using artificial intelligence algorithms. This will permit cable runs and piping to be rerouted and adjusted automatically as the user positions equipment within the ship, using heuristics for routing optimization and redundancy as specified by domain experts. We developed support for these design automation tools, though the tools themselves are not yet fully developed (by team-mates).

Algorithms for the automation of cable routing were implemented within S3D's Naval Architecture Tool based on feedback from consortium members with Naval Architecture experience. Equipment connectivity information from the 2D electrical diagram was exposed through the S3D web service for use by these routing algorithms. Connectivity information could then also be accessed programmatically through the web service by external tools. This

information was used by the routing algorithms to determine how equipment components were logically connected, and to determine the starting and ending points of cables.

Additional capability was added for users to refine the routing by adjusting control points along the cable route.

All developed cable routing features and services were then extended to support routing of piping and ventilation ducts throughout the ship 3D layout. Some support was added for defining service buses and functionality was exposed to allow the user to define these service buses. The intent was to extend the routing algorithms to take advantage of these cableways. Initial research and implementation was done on this but has not matured enough for official release to the user base.

The 3D representations for distribution system components (cables, pipes, ducts) were modified to honor the “Diameter” and “Bending Radius” attribute values to provide a more realistic view of the systems within the 3D space to improve the user experience.

The lengths of cabling, pipes, and ducts are now computed and captured through appropriate attributes on the equivalent equipment item within the 2D view -- for example, the “Pipe Length” attribute on a pipe. These attributes proportionally effect cable impedances, and pipe and duct internal friction. Ultimately, these characteristics are used by the simulation models of the cables, pipes, and ducts within each designer tool to improve the accuracy of computed power flows through cables or mass flow rates through pipes and ducts.

The current implementation of the routing algorithms connects the centroids of equipment 3D models within the 3D scene. Software architecture changes and extensions required to support the specification of equipment port X,Y,Z locations relative to the equipment’s centroid within the 3D space were investigated. A future refinement should utilize this more specific location information to allow endpoints of the distribution components to terminate at port connections. This will further improve the accuracy of pipe length calculations and of the rise and fall of elevation that effect the calculations of pressures and flows within pipes.

Software Methods Supporting Concurrent Design

Continuous (fine grained) collaboration has been achieved in many commercially-available single-focus software tools such as calendars, document processors, spreadsheets, etc… but not so much in multidisciplinary engineering tools, especially those dealing with the complex physical and interpersonal interactions that are necessary for design of ship systems. True concurrency presents two kinds of challenges -- one relative to the user interface and the sharing of data, and a second relative to data management including change-tracking, rollback, and setting of, or resetting to, reference design points. This task addressed the first of these challenges by developing and implementing the methods needed to manage data to provide effective concurrent collaboration among a large team of engineers. The second challenge was partially met in that a design notes tool was developed to track certain changes such as

equipment and attribute modifications. Within each tool the user can now determine exactly how a piece of equipment has been modified. A stand-alone version of this tool has also been implemented that allows users to make queries about all equipment in the design. We had also planned to tackle the rollback and setting of reference points challenge, but as adaptation of S3D for direct Navy use became more urgent, effort that would have been directed to solve the second challenge was instead applied to speed up the task *Integrating S3D with LEAPS*.

A key outcome of this task was development of the capability for multiple users to concurrently develop one (single discipline) ship system [6]. In contrast, the prior version of S3D permitted only one engineer at a time to use any discipline-specific tool (such as the electrical plant schematic editor). A user is now no longer required to lock the schematic before making changes. Extensions were made to the software models captured within the S3D database to allow finer grained tracking of changes made by users. Additional tables were added to the S3D database to formally represent system definitions. Prior to this modification, for each discipline, the definition of each system schematic was stored as one large, self-contained xml document; any change to any part of the system required completely rewriting the entire document. This information was moved from the monolithic document and pushed into the proper corresponding fields within the database. Now user changes to any section of a system schematic are recorded without rewriting the entire xml document. This greatly enhances the collaboration experience.

In order to ensure that each user's view of a design in progress is kept up to date, a publish and subscribe mechanism was implemented. This mechanism pushes design changes out to all users who have subscribed to the particular system.

Development of our multiuser capability was informed by an MSU-led (under subcontract to USC) human factors study that examined typical user interactions and feedback mechanisms during use of the 2014 version of the S3D collaborative web-based environment [5]. The study identified certain features and capabilities that would increase user efficiency, and improve user comprehension of complex multi-disciplinary systems. A total of 17 problems were identified by the design team. The cost of those 17 problems was estimated as a loss of 19.5 minutes of productive design time. A (separately-filed) report on that task described a number of the problems and provided suggestions for ameliorating them through specific improvements to S3D.

Some of those suggestions were then implemented as new features in the S3D environment. For example, the discipline-specific schematic editors now identify all users who are concurrently working on that schematic. All modifications made to the design are propagated to other users and the user making any change is identified. As changes are made to a schematic they are highlighted with the particular color code corresponding to the user making the change.

Tools were developed to summarize and display analysis results for a design or for a set of designs. The tools permit filtering to allow a user to view subsets of the results. Additionally, the tools allow the user to export results to a csv file for further analysis outside of S3D.

S3D users continuosly provided feedback on the usability of the concurrent design tool and helped to evolve the design process to use it more effectively [7]. The added features improved their ability to function in the concurrent environment.

Mission Analysis - Methods, Metrics, and Mission Definition

The objective of this task was to expand the current "design point" analysis capability by enabling time-integrated mission analyses. The *goodness* of any system concept must be assessed in the context of the missions that it will execute. Those assessments must use physics-based Operational Effectiveness Models in order to have confidence in the results (validity) and to ensure an unbiased rational for making decisions [8]. Evaluation of the design point and mission level metrics enables designers to answer questions such as "how much energy storage is needed for a given design?" or "What is the fuel consumption during a mission?" This capability also permits ship concepts to be evaluated across missions or with different payload packages, allowing for evaluation of the platform's flexibility.

A use case study [9] was developed, focused on how to estimate the annual fuel consumption of a ship concept, and the study produced a draft requirements document. The study recommended that the definition of a mission and the analyses of designs against the mission are independent actions and thus two tools were needed -- one to define a mission and another to evaluate performance during the mission.

To evaluate performance through the course of a mission, the original single-operating-point steady-state power-flow solvers were updated to yield a capability to perform a quasi steady-state analysis that produces a time series of steady-state solutions computed for the various operating points during a mission. Power flows are assumed constant (or average) for the duration of each mission segment, and energy quantities are obtained by integrating over the duration of each mission segment. An event scheduling system was implemented to permit components to schedule changes of their operating states.

Events are scheduled by components based on their current operational state. For example, when charging an electrical energy storage module, the module could schedule a "full" event when it expected to reach full charge (which would cause it to stop drawing power from the system). A fuel tank could schedule an event when it expects to be fully depleted (at which time it would stop functioning as a fuel source). The earliest scheduling request is always honored, and when that event is triggered all components re-evaluate the scheduling of any of their internal events. Each component's simulation engine, for each discipline, is responsible for estimating the time when its next operational change will occur. The required changes have been implemented in all of the component simulation engines. More information on the mission analysis framework can be found in [10].

Each of the disciplinary simulation engines in S3D (Electrical, Mechanical, Piping, HVAC), performs their analyses to complete a mission. Every discipline is handled by a different solver instance and each runs independently of others. They do, however, exchange information and depend on the simulation results from each other. As a result, the simulations must often be run for multiple iterations until convergence is reached. Typically, for each mission segment, the simulation engines cycle through 3 to 5 iterations. Criteria for convergence have been implemented, and a tool was designed and implemented that ensures co-simulation of all disciplines until convergence is achieved.

A new error-handling system was created, which allows a model developer to categorize types of errors. For example, errors can produce warnings or they can be "fatal". If fatal, the mission analysis will stop executing and the user will be informed. The new error-handling system has been designed to permit a user (as compared to a model developer) to change whether or not a particular error type is considered fatal. This allows the user some fine control over whether an error causes a mission analysis to terminate, or whether the analysis should continue beyond that event and merely report the error event for later inspection.

A mission creation tool was developed to let users define time-based or geospatial missions with multiple mission segments. A screen capture of the mission definition prototype is illustrated in Figure 1. The image shows the geographical mission definition interface in which the user enters mission waypoints on a map, and identifies the operating conditions during each of the mission segments. The system calculates distance and duration of each segment, from which performance metrics can be evaluated.

A mission analysis tool was created that permits the user to associate a design with a mission for analyses. It includes features that permit the user to configure the design (e.g. turn components on/off or set switch settings) for each mission segment. After the user configures the mission segments he can set the number of iterations for the solver to run through to achieve convergence.

Tools were also developed that permit a user to readily compare designs, and alignments of all equipment in a design, across all missions and mission segments. This allows the user to ensure that the analysis of alternatives is being conducted in a fair manner for all design concepts under consideration.

We conducted an initial investigation into an automated process that transitions concept-level designs to detailed designs. This work led to the development of a prototype tool that helps to move a conceptual design to a detailed time-domain analysis tool that permits deeper analysis using software such as Matlab or VTB. This work will continue under the next research grant.

The mission tools currently do not adapt to events that occur during a mission (e.g. reconfigure switches in the event that a power supply goes offline.) High level controls must be

developed and implemented to handle this adaptation. Additionally, manual definition of the system configurations for each segment is time consuming and error prone. Thus, an automated method is needed for defining optimized configurations for each mission segment in order to meaningfully assess the performance of a design concept. An initial investigation of providing these high levels has begun [11].

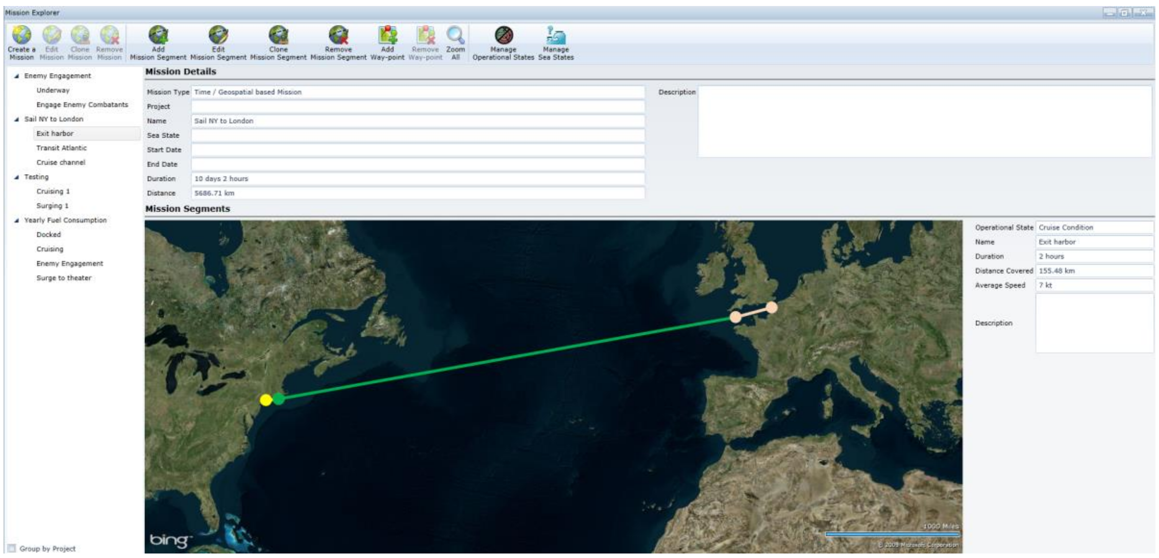


Figure 1: Mission designing tool for S3D showing the geographical mission definition screen

Integration of Distributed Systems

The Navy's early stage design tools lack the ability to design and analyze distributed systems. This significant need drives development of S3D. The initial S3D implementation had some limited capability for designing and analyzing piping and electrical systems. The research reported here aimed to extend those capabilities by:

1. Developing an integrated tool to design ship HVAC systems and analyze heat flows
2. Improving the routing and analytics in the electrical and piping system tools
3. Supporting the efforts of collaborating ESRDC researchers to implement in S3D other advanced or new capabilities for handling distributed systems.

Towards these goals, an HVAC solver prototype was created, and a library of models were developed for the HVAC solver. The HVAC solver is based on the fluid solver used in the piping discipline, but extended to include the concept of air humidity. The solver is capable of determining the water saturation pressure in the air and how much condensation or vaporization occurs with changes in temperature. Other concepts such as flow-rate and pressure that exist in the piping tool also exist here, but no fluid is allowed other than air with humidity levels.

At the moment, the HVAC Designer tool works similarly to the Piping designer. Heat loads, ducts, fans, air handlers, humidifiers, etc. are placed and connected directly in the schematic.

Fluid flow rate, pressure, and humidity are displayed in tool tips. Air temperature is displayed along with a color gradient that indicates the relative temperature based on user-defined thresholds. A more realistic representation of the HVAC system is a compartment-centric tool, where the equipment is placed in compartments, and the compartments are connected in the schematic and cooled, instead of the individual equipment. This compartment centric approach was to follow the implementation of Zones and Compartments under the “Rapid Generation of Concept Designs across Disciplines” task, but that work was deferred in order to focus on the LEAPS Integration work.

Enhancements were made to the distribution systems (cabling, piping, ducts, and shafts) to improve the automated routing capabilities, and to better account for the weight, length, model parameterization, and provide increased accuracy for their overall geometry.

USC assisted Mississippi State University in implementing and testing automated cable sizing algorithms that MSU developed. This technology uses the S3D power flow analysis results to select an appropriate cable or multi-cable bundle from the equipment library and parameterizes the model in the electrical tool.

Research, performed at University of Texas was also transitioned to S3D during this period. An initial version of an intake module developed by UT was transitioned to S3D that enables a user to experiment with various intakes, uptakes, and ducting required for gas turbo-generators. This module helps the user to adhere to Navy standards and ensure adequate performance of the power generation modules.

Significant accomplishments have been made through the combined ESRDC effort in providing advanced design tools for electrical, thermal, and thermal distributed systems. These tools are being migrated to the S3D desktop application, which offer the potential to impact the Navy’s early stage design tools in the near future.

Freedom in the Design Space: Equipment Scaling

Concept designs sometimes demand custom or specially-sized equipment the characteristics of which cannot be easily predicted by reference to historic examples. This is especially true with rapidly-evolving technologies – exactly those that are of most interest to designers of future ships. The task outcome provides ship designers the ability to more effectively explore the design space free of the constraints of the existing sets of equipment. In addition, this capability enables all stakeholders and engineers to evaluate, compare, and contrast future technologies and identify promising R&D targets. Finally, this will enable, with further development, varying components parameters to develop multiple design variants in a set based design approach.

This task developed and implemented a generalized framework for equipment scaling within the design tools, permitting both experienced engineers and laymen the ability to experiment with the incorporation of new technologies and families of existing equipment in

order to realize a ship design. An intuitive interface was developed that permits the user to scale up or down equipment within some constraints.

We demonstrated this frame work by implementing scalable models for electric ac motors and generators, based on algorithms developed by ESRDC researchers at Purdue University. The algorithms employ new methods for estimating scaling parameters by reference to physics-based estimates of Pareto-optimal designs.

There is a continuing need to develop additional scaling algorithms for other components so that S3D can broadly support flexible design explorations.

Rapid Generation of Concept Designs across Disciplines

The ESRDC-developed process for early stage ship design includes a brainstorming phase that aims to rapidly develop multiple very high-level concepts that will subsequently be fleshed out in each of the disciplines [11]. During the FY13 ESRDC Collaborative Design Workshop the design team used S3D's NavArch tool to develop these design concepts and in the process, the team identified a need for these new capabilities:

- Capacity to quickly clone a concept template, and to define and link components to logical groupings (e.g. ship work breakdown structure (SWBS) number) or zones, and the ability to pass those groupings between the disciplinary tools was deemed essential to rapidly advancing the design.
- Support the brainstorming process by eliminating a need to manually parameterize components to a level that is un-necessarily deep for this first fractional design step.

The first objective was partially achieved. Users can now clone designs or projects via a simple two-click process. Also, the tools, database, and models were modified to permit groupings by SWBS number. Each component can now be assigned a SWBS number and equipment lists and analysis results can be filtered by SWBS number.

Grouping by zones or compartments, rather than by SWBS, is more complicated because those groupings involve the mapping of the group onto either the 3D geometry of the ship hull, bulkheads, decks, and components, or onto some other non-spatial logical relationship that defines a zone. Research on how to effectively do the mapping with minimal human effort was begun. However, at the advent of the LEAPS Integration task this effort was deferred due to the high manpower requirements for LEAPS integration. Also, since LEAPS/ASSET already implements the notion of zones, it was more prudent to work with that existing approach to zones rather than to develop an independent approach to implementing zones. Implementation of zone definition methods will restart when it fits within the LEAPS integration timeline.

In addition to the two goals stated for this task, USC also supported Florida State University's work towards providing a design guidance feature in S3D that fits within the rapid

development of concept designs. FSU's advances to the design guidance tools were incorporated into the S3D environment. These now allow the user to create a document repository for military specifications, research papers, and industry standards that can be intelligently searched to find answers to user questions about a ship design detail. Several on-going research activities in the ESRDC require the ability to extract from S3D the topology and bill of materials for a design concept in order to provide additional processing or analysis that is external to the S3D environment. We have enabled this by developing a tool that connects to the S3D environment, extracts the data, and presents it in a way that permits evaluation of the design and the opportunity to change the design and push the changes back into S3D. Other requirements that were identified and addressed in this area were improvement to the exporting and importing processes of S3D in order to provide capabilities for post processing by using standard Excel spreadsheets. Emphasis was specifically placed on capturing analysis results this way.

Advances to the tools greatly improve the ability to rapidly create and organize system designs and to view and analyze performance data. Additional capabilities are yet required to enable representation of compartmentalization that is needed for HVAC analyses.

Using S3D to Demonstrate/Evaluate MVDC Technology Advances

The objectives of this task were to use S3D to demonstrate the potential benefits of new ESRDC developed technologies, to expose the S3D design tools to the Navy and Academic communities, and to elicit feedback on S3D to guide its further development.

A baseline model of a 20kV MVDC ship was built using the S3D Collaborative Design Environment. This baseline model was used, and expanded upon, in the study "Using S3D to Analyze Ship System Alternatives for a 100MW 10,000 ton Surface Combatant" [13] under ONR grant N00014-14-1-0668. The combined work examined the weight, volume, and fuel consumption for the baseline, and for several variants that:

- Used alternative power converter technologies,
- Used high speed generators for power generation,
- Used an alternative electrical system topology.

A master's student used S3D to design a range of naval vessels from a traditional naval destroyer to a state-of-the-art warship fueled by liquefied natural gas. The pros and cons of ship design using S3D were evaluated in these applications, and recommendations for areas of improvement were captured and addressed. The study also evaluated traditional ship design methods including design spiral and set based design, as applied in S3D, and proposed a hybrid design method as being more effective when using real time collaborative engineering tools like S3D. [7]

We provided a 5-day S3D Training and Demo Workshop in January 2016, in Philadelphia, PA. The workshop was designed to inform participants about S3D development efforts, and to

enable participants to evaluate S3D for use in upcoming Navy ship concept studies. Participants included 33 from the Navy ship design community, 4 from Industry, and 6 from academia. [14].

At the conclusion of this project in March 2017, we were also providing S3D training to Georgia Tech researchers, and we continued to provide ongoing training and support for programmatic extraction of data from S3D in order to enable the GT team to perform additional analyses of ship designs using GT's native tool set.

Feedback from S3D users and from workshop participants has helped to guide S3D development priorities and has led to improved usability. For example, users in the ship design study identified a need to have greater access to analysis results, so a feature was added that permits users to export all analysis results so that they can be consumed by external analysis tools.

Integration with LEAPS

S3D was developed to fill the Navy's stated need to expand simulation capability in early-stage design tools. S3D intends to facilitate the definition and simulation of shipboard distributed systems, and to analyse the interactive and ship-wide effects of distributed systems through which energy flows. To augment the Navy's existing capability, we are in the process of refactoring S3D so that it can better coordinate with the Navy's existing standard design data repository (LEAPS), so that LEAPS can serve as S3D's inherent, integrated data repository. We have made great strides towards completion of this refactoring, but we still have a long ways to go. This manpower-intensive task assumed a higher priority and larger scale than was originally envisioned, so it detracted from performance in some of our other investigations. The difficulties of LEAPS integration was complicated by our reliance on a large group of student-level software developers who were still developing their competency at C++.

LEAPS is the Navy's product model repository that is used to capture product metadata, and is intended to be the central repository of ship design information throughout the design cycle, ship production, and eventually through the entire life cycle of the ship [15]. Analysis tools currently used by the Navy incorporate translators which allow for the extraction and insertion of data into LEAPS. The Navy has made a significant investment in its tools and in ensuring that its in-house analysis tools can insert and extract information from this repository. Figure 2 shows where S3D fits into the Navy's suite of early stage design tools.

The objectives of this task were to:

1. Modify S3D to use LEAPS as the integrated data repository
2. Port S3D capabilities into a stand-alone analysis tool that provides design and simulation capabilities for shipboard distributed systems that will function with the Navy's suite of design tools.

The initial phases of the S3D/LEAPS integration project involved analysis and comparison of the two data structures to determine required changes to each. This report describes the

results of that comparison; specifically, the investigation of the baseline structure of the two databases including such things as definition of data types, relationships between database tables, and definition of units; and the analysis and comparison of the structures of the product meta-models, leading to a plan for the organized integration of the meta-models. [16, 17]

To expedite the integration of LEAPS with S3D, an interoperability layer was added to LEAPS libraries to expose them for use in C#. The cloud software classes in C# that represent the database objects were ported over to the desktop to be used for translating between S3D data format and LEAPS format. These software projects allow the S3D code to make calls directly into LEAPS via a C# managed code library that accesses the LEAPS API. This permits some experimentation with the LEAPS database in order to understand how it can be effectively used with S3D. The initial implementation allowed for the opening and closing of a LEAPS database. LEAPS databases can be opened on the user's local machine, or from a network share. A LEAPS database was also added for testing purposes. Additionally, some consideration was given to the possibility of replacing the existing SQL Server backend serving the S3D Cloud with a LEAPS database, but the pessimistic locking strategy of LEAPS would not make this practical. Changing this strategy would require significant modifications to the current LEAPS database architecture. We established making calls from the managed C# code of S3D directly into the C++ LEAPS code library and read data from the LEAPS database. The major hurdle -- how best to integrate S3D and LEAPS -- was thus resolved. The asynchronous, multi-threaded, concurrent, and multi-user nature of S3D has led to a particular software architecture and data model that directly supports this behavior. Emphasis in S3D is placed on ensuring the integrity of the design through referential integrity constraints, speed of the application by committing small granular updates, and the overall performance of the application as is typically expected in an online transaction processing (OLTP) type application.

We created a tool to automate the mapping of the equipment in the S3D catalog to ASSET equipment. The tool expedites conversion of an ASSET generated ship model into a set of equipment that can be inserted into an S3D system schematic as a ship concept is defined.

Three releases of a desktop version (non-web-based) of S3D were developed and provided to the Navy for evaluation. The first, S3D Ver 1.0, was delivered to NSWC in Jan 2016, and it was used during the S3D Workshop at Philadelphia in Jan 2016[14]. That release included integrated electrical, mechanical, and thermal system design and analysis, it used LEAPS as its persistent data store, and it provided a mapping tool that relates S3D equipment and their attributes to LEAPS equipment and corresponding properties, written in C#. The second release, V 1.2, was delivered in Oct 2016, and contained new component models, improvements to existing models, and it resolved several noted issues. The most recent release, V 2.0 (alpha), was delivered in June 2017 under a subsequent ESRDC grant, but a significant amount of the development was performed under this grant. V 2.0 (alpha) represented a significant improvement over the earlier releases. It was a native LEAPS application written in C++, which is the Navy's preferred language for the LEAPS design tools. The code conformed to Navy

standards, it integrated with the Navy's LEAPS database, and it included user interfaces for schematically defining electrical, mechanical, piping, and HVAC systems. Simulation models and solvers for this release were available as C# code modules to provide analysis capability. Subsequent work will move the simulation models and solvers from C# to C++ so that these can become fully integrated.

Significant effort was also committed to documenting all tools and models. Help files that describe the use and the mathematical implementation of S3D models were written for roughly 200 ship system components. This documentation is used by Navy personnel in support of further code development and in support of the personnel who are evaluating the S3D product.

As of the end of this grant, further development is required to make S3D fully functional for Navy ship design work. Many extant features in the cloud version, such as the mission analysis capability, remained to be ported to S3D V2. New features under development by the ESRDC, such as the use of templates for rapid system design, are yet to be implemented in S3D.

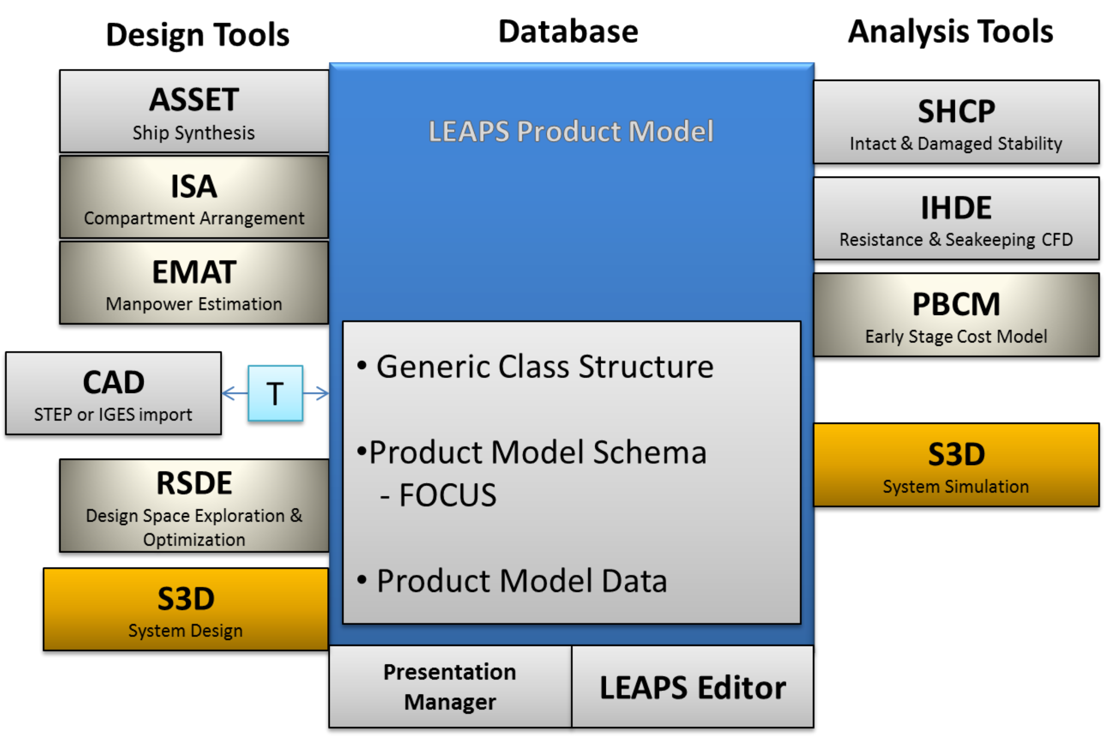


Figure 2 Illustration of how S3D fits into the Navy's suite of early-stage design tools, both on the input side as a mechanism to define system concepts, and on the output side as a tool for analyzing the performance of system concepts.

Power systems control and modeling

Applications of Impedance Identification to E-Ship System Control and to PHIL Simulation

The research performed in this area culminated in the Ph.D. dissertation "Applications of Impedance Identification to Electric Ship System Control and Power Hardware in-the-loop Simulation" by Jonathan Siegers [18]. The following description of that work is taken from the dissertation.

> Recent advances in power semiconductor technology, controls, and power converter topologies have resulted in the increasing application of power electronics in power distribution systems. Power electronic enabled distribution systems have inspired a renewed interest in DC distribution architectures as an appealing alternative to traditional AC methods due to the significant performance and efficiency gains they offer. However, the notional power electronic based DC distribution system is a complex and extensively interconnected system consisting of multiple power converters. As a result, a number of system-level challenges related to stability arise due to interaction among multiple power converters. In addition, the power distribution system is likely to undergo configuration variations as the system is subject to component upgrades, changes in power sources and loading, and even contingency scenarios involving fault conditions. The design of this type of system is difficult due to the general lack of proper analysis tools and limited understanding of the problem.
>
> To address these design challenges, an approach to control design that accounts for converter interactions and allows for impedance based control is proposed. The use of impedance monitoring via wideband impedance identification techniques provides interesting opportunities for the development of a robust and adaptive control strategy. Power converters within the system can be adaptively adjusted to track changes in the system bus impedance, enacting revised control strategies with the intent of stabilizing the system as its dynamics evolve over time.
>
> Secondly, the use of Power Hardware-in-the-Loop (PHIL) simulation is investigated for early system testing. As parts of the distribution system become available in hardware, it is desirable that they be evaluated under realistic system conditions. PHIL allows for advanced studies to be performed on system interactions by virtually coupling a real-time software simulation of electrical components to a physical piece of hardware through the use of an interfacing amplifier and appropriate control algorithm. Use of a PHIL test platform allows for system interaction studies to be performed early on in hardware development and provides an enhanced ability to study potential system-level problems and develop suitable solutions. Wideband

impedance identification is utilized to complement the PHIL simulation, providing additional characterization of the hardware under test as well as critical information that is used to ensure stability and fidelity of the PHIL simulation test bed.

Details of the methods investigated and their results can be found in [18,19,20,21,22,23]

Impedance-Based Control

Allowable Impedance Region and PFF Control Design

The conceptual multi-bus system shown in Figure 3 has been studied. Stability of the overall system can be analyzed based on the individual bus impedances, which consists on the parallel combination of all source and load subsystems seen from each dc bus. The Passivity Based Stability Criterion (PBSC) provides a sufficient condition for stability; if each of the bus impedances are found to be passive at all frequencies, the system is stable. This criterion was proved to be effective in analyzing the overall stability; however it does not provide any information regarding the dynamic performance and a system satisfying the PBSC might exhibit undesirable oscillations during transients. To overcome this limitation, the Allowable Impedance Region (AIR) has been proposed; this concept is also based on the Nyquist contour of the bus impedances and it states that if the contour lies completely inside a specified region in the *s*-plane then the system will exhibit a minimum damping for oscillations.

The AIR was also implemented for design of a stabilizing controller, leading to the development of damping impedance required to achieve desired dynamic performance. This damping impedance is then inserted into the system via Positive Feed-Forward control. Analysis of the bus impedances resonance leads to the appropriate PFF implementation on the system.

To validate the proposed method, the 2-bus system depicted in Figure 3 was built in the laboratory. First, the bus impedances were measured and compared to an analytic model as in Figure 4. Notice that the system is stable since the bus impedances are found to be passive at all frequencies. However, Bus 1 exhibits a prominent resonance which indicates poor damping for oscillations. Based on transient specifications, the Allowable Impedance Region shown in Figure 5 is found. The Nyquist contour of the measured bus impedances (dashed lines) are entirely in the left half plane but outside the allowable region confirming that the system is stable but poorly damped. After implementing the PFF control, the Nyquist contour of the bus impedances (solid lines) lay entirely inside the allowable region, providing minimum damping for oscillations. This is verified with the experimental time domain results shown in Figure 6.

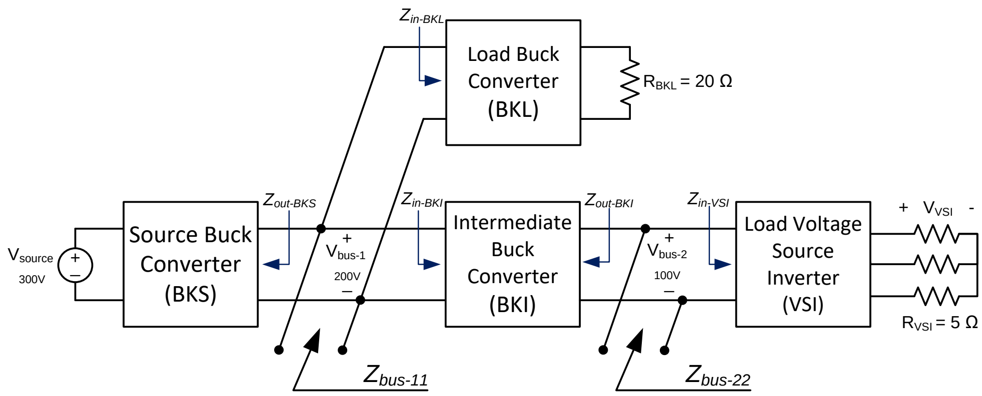
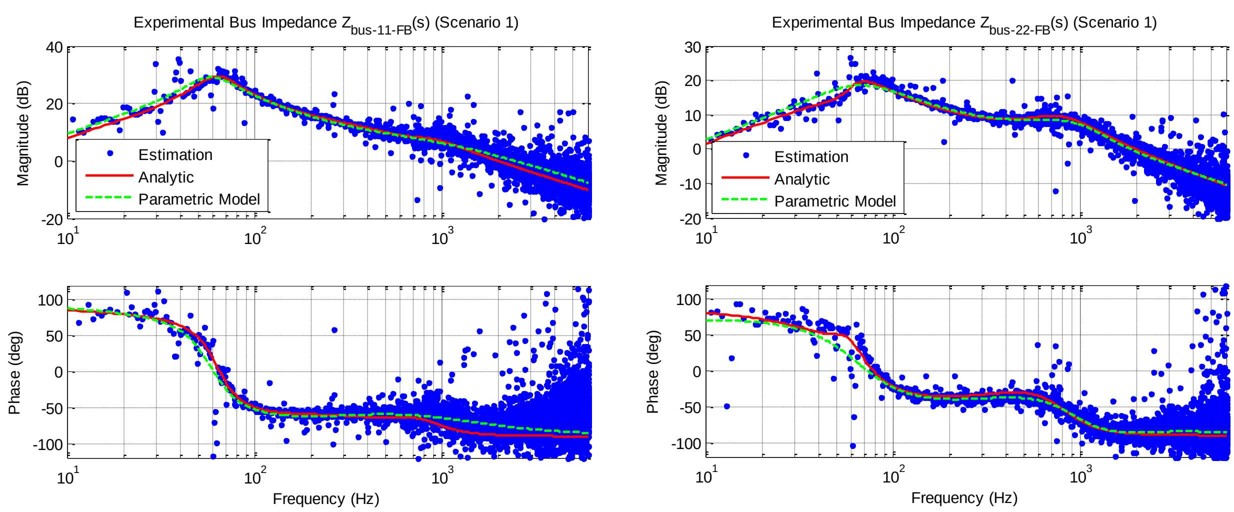


Figure 3 Scaled notional multi-bus MVDC distribution system



(a) (b)

Figure 4 Experimental Bode plot of (a) bus 1 estimated impedance and (b) bus 2 estimated impedance. System operating under FB control only

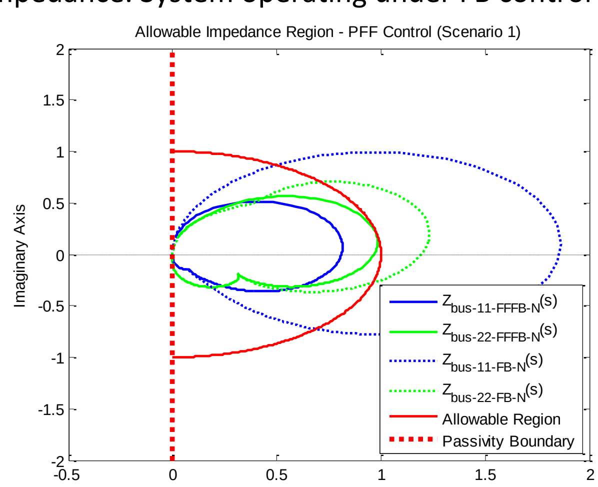


Figure 5 Nyquist plot of normalized bus impedances and Allowable Impedance Region. System operating under FB control only (dashed) and FFFB control (solid)

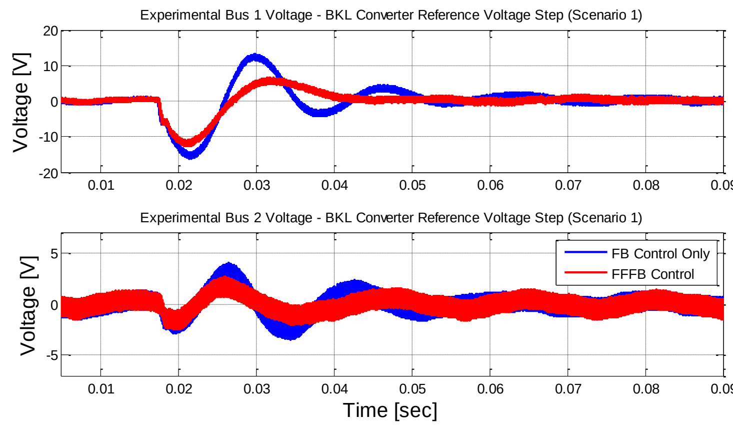


Figure 6 Experimental time domain results of AC coupled bus voltages under (blue) FB control and (red) FFFB control during BKL voltage reference steps

Further details can be found in [24,25,26,27,28,29,30]

Develop a framework to evaluate systems of distributed energy storage

We developed and demonstrated a multi-agent system (MAS) distributed control to coordinate systems of power electronic converters with the goal of achieving flexible management of energy flow while achieving high robustness. A distributable optimization method suitable for real-time coordination was developed that can be distributed for parallel computation by MAS type control systems. Decomposition of the optimization algorithm allows for very fast convergence to a solution. The work points to gains in overall system control functionality that can be achieved if communication based control systems are selected as a requirement for the future fleet. The work has the potential to provide future Naval platforms a power system control that is more survivable, and flexible than the usually-used hierarchical system control methods.

Details of the control methods can be found in [31,32,33]

Fault Management in Fault Current Limited MVDC Systems

This task extended our prior work on fault management (based on a process of rapidly de-energizing, reconfiguring, and re-energizing the power network). In new work, we showed how each entity connected to the dc bus, including current-limiting power converters and non-load-breaking disconnect switches, can autonomously detect, identify, and appropriately react to the presence of a short-circuit arcing fault based only on its own local observations of voltage and current. The range of coverage was extended to include arcing faults with stochastically varying impedances up to 4 Ω, even under time varying load conditions (1 pu to 2 pu), by dynamically adjusting the tripping thresholds of bus-tied components (power converters and bus segmentizing contactors). Successful operation is predicated on enforcement of defined ramp rate limits for all power converters connected to the main MVDC bus. Details can be found in [34,35,36,37]. For the Navy, this work provides part of the groundwork for building

an MVDC system that does not depend on functionality (survivability) of a ship-wide communication network to protect the main power bus and that does not require the use of load- or fault-breaking dc current interrupters (and their associated size and weight penalties).

SiC Converter Modeling for System-Level Studies in S3D

SiC converter size, weight and thermal load decrease as technological advances provide improved components to be used for converter design. This is pictorially represented in Figure 7: advances in SiC device performance, magnetics, thermal management, and so on allow reduction of the total converter footprint. Therefore, it is critical to be able to project future SiC converter performance as a function of future technological advances. This can best be achieved by using a physics-based modeling approach, which relates device performance to physical parameters, from current state-of-the-art all the way to theoretical limits due to materials and processes. For example, SiC MOSFET performance is presently limited by achievable bulk mobility and inversion channel mobility, where significant improvements are still possible.

The end result of the SiC converter modeling is shown in Figure 8: a complete SiC converter model with estimation of total converter footprint based on SiC device characteristics, passives and thermal management system. The SiC device performance has the largest impact on converter characteristics, because most losses occur there and switching frequency determines passive component sizes (Figure 9).

Simple and accurate circuit-simulator compact models for gallium nitride (GaN) high electron mobility transistor (HEMT), SiC MOSFET, and SiC Schottky diode have been developed and validated under both static and switching conditions. Simulation models have been built in Pspice software tool, considering the parasitic elements associated with the PCB interconnections and other components (load resistor, load inductor and current shunt monitor). The Pspice simulation results have been compared with experimental results. The comparison shows good agreement between simulation and experimental results under both resistive and inductive switching conditions.

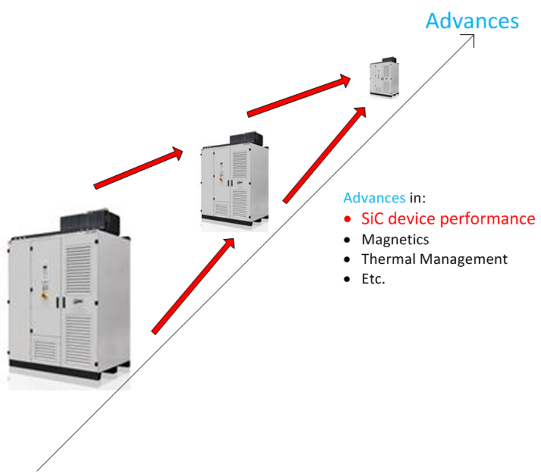


Figure 7 SiC converter scaling as a function of technological advances

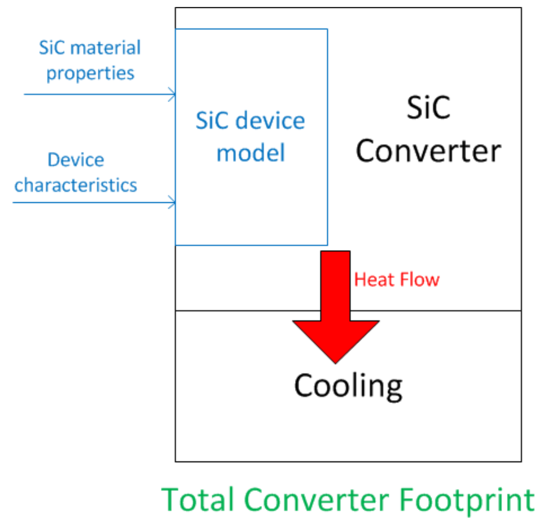


Figure 8 SiC converter total footprint includes SiC devices, other electrical components such as filter elements, and thermal management

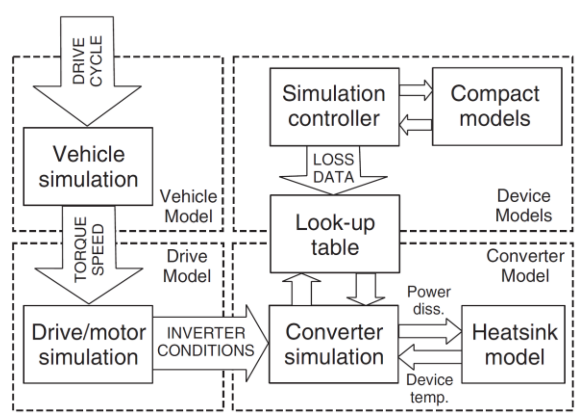


Figure 9 Possible implementation of SiC device loss models as a function of physics-based compact models as described by the PI in [38] for a vehicle motor drive application.

Details of these models and how they were derived can be found in [39,40,41,42,43,44,45,46]. Future work will make these power converters models available to the Navy in the form of improvements to cabinet-level models within the S3D toolset.

Advanced cooling methods for ship systems

Following is a summary of the work performed under these cooling methods tasks. For more details see publications: [47,48,49,50,51,52,53,54,55].

System-Level Thermal Modeling

This task supports ESRDC work in the area of system level modeling and integration of advanced cooling/thermal management for next-generation ships. This is a collaborative effort between MIT, FSU, and USC in which the team is developing high fidelity system level thermal

models for Navy ships. USC's task is to provide validated model equations (correlations) for high heat flux thermal management solutions. USC focuses on providing an experimental database to validate and improve MIT's numerical efforts.

USC continued identifying high performance two-phase cooling technology for the thermal management of high power electronics on board of future all-electric ships. Test results showed that the high heat flux methods are scalable. That is, the methods can be effectively applied to enhance cooling of large surfaces. We developed experimentally validated models that can well predict heat transfer coefficients and can be integrated into system-level simulation tools for early stage thermal design. Two phase cooling component models are in the queue to be implemented in S3D.

In support of MIT's effort, we developed and provided experimental data for two-phase flow with single-phase heat transfer (nitrogen-water flows) to benchmark the code developed by MIT. Nitrogen-water two phase flows in smooth microchannels were systematically studied to characterize the heat transfer, pressure drop and instability performances with flow mechanisms. Experiments were conducted with water superficial velocity ranges from 0.06 m/s to 0.6 m/s and where the nitrogen gas quality varied from 0.0025 to 0.475. Flow visualizations were performed along with the experiments to reveal the gas-water two phase flow mechanism. The flow field consisted of a microchannel array of five parallel channels (W=220 µm, H=250 µm, L=10 mm). A thin film heater and three thermistors were integrated on the backside of the microchannels. Average heat transfer coefficient, average pressure drop, transient pressure drop, transient wall temperature and two phase flow patterns were systematically collected, analyzed and provided to MIT.

We also provided to MIT a series of data for boiling flow in microchannels with various configurations, using de-ionized water.

Modeling and Development of Core HVAC Models and Highly Efficient Vapor-Compression Refrigeration Cycles for Ship HVAC System

The development of an HVAC tool within S3D to handle air-cooled loads was identified as one of the priorities for extending the capabilities of the collaborative design tool. The overall goal of this task was to identify and model efficient condensers and evaporators for vapor-compression cycles so that these technologies could be considered in ship design concepts. The focus was on lighter (smaller) and more efficient vapor compression systems. Our early results showed that coefficient of performance (COP) can be enhanced up to 20% when the heat transfer coefficients of evaporator and condenser increase by one magnitude.

As part of this task, we demonstrated significantly enhanced evaporation on partially wetted nanoporous surfaces that were created by functionalized multi-walled carbon nanotubes, which are composed of hydrophobic pristine surfaces and hydrophilic carboxyl and

hydroxyl groups. These novel surfaces exhibit the advantages of both hydrophobic and hydrophilic characteristics and are ready for scaling up.

The experimental data and predicted correlations for evaporating heat transfer coefficient (HTC) as a function of superheat temperature were developed. It is apparent that the trend predicted by all of the four correlations at different flow rates are well matched with the experimental data. Mean absolute error (MAE) was used to evaluate the difference between the experimental results and predicted HTC values for each correlation.

Highly efficient condensation surfaces have been developed and demonstrated by our team. Heat flux and heat transfer coefficient of dropwise condensation are shown to be significant dependent of the surface subcooling, which is the driven force for steam condensation. Surface modification was shown to be an effective method to enhance steam condensation heat transfer. Although some surfaces modified to be hydrophobic can enhance steam condensation heat transfer coefficient by changing the condensation mode from filmwise to dropwise condensation. However, when the dropwise condensation on these surfaces reverts to filmwise condensation or the condensate flows as a rivulet, heat transfer performance decreases significantly. In our experimental study, we used NiO atomic layer deposition coating, self-assembled monolayers (SAM) to modify the surface and hydrophobic-hydrophilic hybrid surface to enhance steam condensation heat transfer on tubes. A series of dropwise condensation correlations have been developed.

Development of High Heat Flux Cooling Strategies

The next generation of US Navy's all-electric warships with emerging high power sensors and weapons systems will present two dominant thermal management challenges: 1) surface heat fluxes will likely approach or exceed 1000 W/cm^2 [53]; and 2) thermal loads will be 5-10 times higher than in today's surface combatants [57]. Traditional air and single-phase liquid cooling technologies cannot meet the requirements for high heat fluxes (300~1000 W/cm^2), for temperature uniformity (i.e., extremely high heat transfer coefficients), and for system integration (compactness).

Numerous novel high heat flux cooling concepts have been developed in 6.1 research programs. These include "Nano and micro reentrant cavities for enhanced micro channels boiling", "System-level approach for multi-phase, nanotechnology-enhanced cooling of high-power microelectronic systems", "High-frequency self-sustained two-phase oscillation mechanism", etc. For example, the high-frequency self-sustained two-phase oscillation mechanism was demonstrated by Li and Khan at the University of South Carolina (USC) [58,59]. This mechanism can generate and sustain strong mixing by enabling rapid bubble growth and collapse inside microchannels in a passive and controllable manner. Unprecedented performance of flow boiling in terms of critical heat flux (CHF) and heat transfer coefficient (HTC) were achieved. Specifically, a CHF of 1025 W/cm^2 with averaged HTC > 100 kW/m^2-K were experimentally demonstrated. In addition, the pressure drop that determines the

pumping power is reduced by approximately 90% compared to inlet restricted microchannels. However, this promising high heat flux cooling concept has been only demonstrated in a 1 cm by 0.2 cm heating area in Si substrates. It is essential to scale up these demonstrated novel cooling concepts to accommodate the thermal management needs in US Navy's all-electric warships at system level.

The objective of this task was three fold: First, transfer already-demonstrated high heat flux cooling concepts to substrates such as SiC and metals as needed for applications in ship-scale power electronics. Second, scale up these concepts to large working areas for system level applications. And last, develop robust and experimentally validated thermal/hydraulic models of these two-phase high heat flux technologies for use in the S3D early-stage ship design environment.

To that end, a test setup was established for two-phase heat transfer and flow modeling validation in USC. The experimental data obtained from our test setup is close to the Nusselts' theory in filmwise condensation. Further improvements are being made to improve the measurement accuracy.

An initial design of a two-phase cooling plate for a power converter has been simulated on a 5 mm by 5 mm chip. Compared to a single-phase cooling plate, our simulation showed that two-phase can substantially reduce the wall temperature up to 40 C for a working power of 80 W. To test two-phase cooling for a power electronic module, we designed, fabricated, and populated a DBC power module prototype. An additional feedback control and sensing PCB is being developed to allow experimental validation of the advanced cooling approach.

Additionally, we have experimentally validated two-phase models that have been developed to predict required flow rate and pumping power.

Conclusions

Our research produced significant progress in the development of **early-stage ship design tools.** The two main objectives were to enhance functionality of the distributed, collaborative S3D early stage design environment, and to define a process for integrating S3D technologies into NSWC's LEAPS-centered toolkit. Several major functional objectives were accomplished including: development of a capability to exercise and evaluate designs against missions, improvements to tools for designing distributed systems, and providing support for our ESRDC partners. Furthermore, we used the developing S3D environment to evaluate and demonstrate the advantages and disadvantages of several advanced ship technologies.

The LEAPS integration effort made greater progress and used greater resources than we originally planned. We released a functional application compliant with LEAPS ontology and using LEAPS as the data repository. This application does not yet have all of the functionality that is in the cloud version, and work to port that functionality is ongoing.

The accelerated effort on LEAPS integration detracted from completing some of the development work originally planned. We enabled analysis against a mission, but the year three plan to explore methods to automatically configure the ship systems was delayed. We also delayed implementing the ability to define zones/compartments and to group components within those zones. These delayed tasks are continuing under our current grant.

Research in **Power Systems Control and Modeling** accomplished five main objectives. It:

1. Improved the methods for measuring power system impedance so that impedance characteristics can be considered and used to improve the control of ship electric systems, and similarly to improve the performance of power hardware in the loop simulations.
2. Developed new impedance-based control methods for ship electric systems.
3. Developed a framework for evaluating the performance of distributed energy storage concepts
4. Improved the reach and understanding of breaker-less, control-based methods for managing short circuit faults in MVDC Systems.
5. Developed models of SiC-based electronic power converters that are appropriate for system-level studies.

The research in control methods continues as within the ESRDC towards developing a holistic control approach for an MVDC electric warship. The approach addresses self-awareness, power flow management, protection, and stability. The methods developed under the research herein provide key resources to achieving that holistic control approach.

Research in **advanced thermal management** accomplished six main objectives. It:

- developed S3D-compatible models for state-of-the-art heat exchanger and air cooling technologies based on surveys of the best published models and correlations.

- in collaboration with FSU & MIT, it developed a core group of models of HVAC components, and of highly efficient vapor-compression refrigeration cycles for ship HVAC systems.
- Developed a hardware testbed for two-phase heat transfer and flow as needed to calibrate and validate system-level models. Data from the testbed proved that heat transfer rates were close to those obtained by applying Nusselts' theory in filmwise condensation.
- Developed a reference simulation model of a two-phase cold plate for an electronic power converter that showed the possibility to substantially reduce the wall temperature - by up to 40 C - compared to single-phase cooling.
- experimentally validated models of two-phase heat exchangers including correct prediction of required flow rates and fluid pumping powers.

The developing designs for advanced ship thermal management systems continues in collaboration with MIT & FSU investigating the application of heat transfer corridors and thermal systems control methods. Additionally, we plan to demonstrate advanced two-stage cooling technologies to the cooling of electronic power converters for ship electrical systems.

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University of South Carolina as part of the Electric Ship Research and Development Consortium developed several technologies and methods advancing the state of the art in three broad areas: 1) early-stage ship design tools, 2) advanced electric power systems control and modeling, and 3) applications of advanced cooling methods in electric ship systems.

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